NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4203

FLIGHT INVESTIGATION OF EFFECTS OF ATMOSPHERIC TURBULENCE AND MODERATE MANEUVERS ON BENDING AND TORSIONAL MOMENTS ENCOUNTERED BY A HELICOPTER ROTOR BLADE

By LeRoy H. Ludi

Langley Aeronautical Laboratory
Langley Field, Va.

Washington
February 1958

iT

NATIONAL ADVISORY COMMITTEE FOR AERONAUTIC

TECHNICAL NOTE 4203

FLIGHT INVESTIGATION OF EFFECTS OF ATMOSPHERIC TURBULENCE AND MODERATE MANEUVERS ON BENDING AND TORSIONAL MOMENTS ENCOUNTERED BY A HELICOPTER ROTOR BLADE

By LeRoy H. Ludi

SUMMARY

Flight tests have been conducted with a medium-size single-rotor helicopter, of which one blade was equipped with strain gages, to determine the relative effects of atmospheric turbulence and moderate maneuvers on the periodic rotor blade moments.

The results indicate no significant increase in the total blade moments due to atmospheric turbulence or moderate pull-up maneuvers which produced center-of-gravity acceleration increments of less than about 0.15g (where g is the acceleration due to gravity). Because about 99 percent of the total flying time is spent at acceleration increments below 0.15g, the principal part of the flying time is thus found to be unaffected by atmospheric turbulence or moderate maneuvers. Therefore, the time spent in the various flight conditions, as determined by the NACA helicopter VGHN recorder, can be used at least for that part of the cumulative fatigue analysis involving the largest number of cycles in distinction to the largest stresses. Atmospheric turbulence and moderate maneuvers which resulted in center-of-gravity acceleration increments above 0.15g produced some increased moments which are of interest, particularly in the higher harmonics.

INTRODUCTION

The moments experienced by a helicopter rotor blade may be divided into two categories with regard to cumulative fatigue. These categories are (1) high moments repeated often enough to contribute to fatigue and (2) low- to moderate-level periodic moments applied continuously in routine flying (even in calm air). The high moments repeated often enough to contribute to fatigue could at times be very important, but their treatment is not the primary purpose of this report. The low- to moderate-level periodic moments applied during a large number of cycles are universally a matter of concern and are the subject of the present paper.

NACA helicopter VGHN recorder surveys provide information on airspeed, center-of-gravity acceleration, altitude, rotor rotational speed, and the percentage of total flying time spent in each condition during actual operations. Reference 1 illustrates such a survey in which it is shown that less than 1 percent of the total flying time is spent at acceleration increments of 0.15g or greater. The NACA helicopter VGHN recorder does not directly measure blade moments but rather specifies the flight conditions. Therefore, these time-spent surveys must be used in conjunction with moment measurements obtained during prototype tests for specific flight conditions. These sources of information can be used together to determine the contributions to fatigue of almost all the moment cycles occurring, provided that ordinary gusts and control motions do not produce additional periodic blade moments significant to fatigue calculations.

Experimental tests of a full-scale rotor in gusty air at a very low forward velocity (ref. 2) revealed that the effects of gusts on rotor blade bending moments appear to be secondary when compared with downwash effects. Reference 3 presents a preliminary investigation of the effects of sharp-edge gusts on the flapwise vibratory bending moments of small model rotor blades having either fixed-at-root or teetering blades. Reference 4 indicates that there is an increase due to gusts in the normal acceleration of a helicopter as the forward speed is increased. Since information was lacking on the blade moments encountered by a rotor under actual flight conditions, the primary purpose of the present investigation was to determine whether atmospheric turbulence or control motions do cause increased periodic blade moments. More specifically, the purpose of the investigation discussed herein was to determine the effects of atmospheric turbulence and control motions, which produced center-of-gravity acceleration increments of less than about 0.15g, on the rotor blade moments.

In order to obtain the information required, a blade of a single-rotor helicopter was equipped with strain gages which measured flapwise and chordwise bending and torsional moments. In determining the effects of atmospheric turbulence, several flights were made in both smooth and rough air. The tests were made in level flight at various forward speeds. The effects of control motions were determined by performing moderate cyclic, collective, and combined cyclic-collective pull-up maneuvers. The results of this investigation should help to establish procedures which will aid in the design of future rotor blades, hubs, and control systems. It is also expected that these results will prove to be indicative of the results that might be obtained with most present-day helicopters.

SYMBOLS

a	slope of curve of section lift coefficient against section angle of attack (assumed equal to 5.73), per radian
b	number of blades per rotor
c	blade chord, ft
I_1	mass moment of inertia of blade about flapping hinge, slug-ft^2
R	blade radius measured from center of rotation, ft
V	true airspeed, knots
V_i	indicated airspeed, $V\sqrt{\rho/\rho_0}$, knots
γ	mass constant of rotor blade, $c\rho aR^4/I_1$
ρ	mass density of air, slugs/cu ft
ρ_0	standard mass density of air, 0.002378 slug/cu ft
σ	rotor solidity, $bc/\pi R$
Δa_n	acceleration increment, g units

TEST EQUIPMENT AND INSTRUMENTATION

The single-rotor helicopter used in the present investigation is shown in figure 1, and its principal dimensions and approximate physical characteristics are listed in table I. The helicopter has conventional pilot controls: stick, pedals, and collective-pitch lever. Each rotor blade has offset flapping and drag hinges.

In addition to the NACA helicopter VGHN recorder, the helicopter is equipped with other standard NACA recording instruments with synchronized time scales which measure airspeed, altitude, manifold pressure, rotor rotational speed, pilot-control positions, angular velocities about the three principal inertia axes, and acceleration at the center of gravity of the helicopter.

Resistance-wire strain gages are mounted on the spar of one blade to form complete bridges at 14 percent and 40 percent of the blade radius. The strain gages at the 40-percent-radius station measure only flapwise bending moments, whereas the strain gages at the 14-percent-radius station measure flapwise and chordwise bending and torsional moments. The strain-gage installations on the rotor blade are shown in figure 2. Two spanwise stations were considered adequate for this investigation because only comparative flight results were desired. The signals from the blade strain gages are brought down from the rotating members of the rotor by the use of a slipring assembly. The strain-gage information is recorded by an 18-channel Consolidated oscillograph. The natural frequency of the galvanometer elements of the oscillograph is approximately 53 cycles per second, and it is 0.7 critically damped. This frequency and damping resulted in a response curve that is flat to within ±5 percent up to about 30 cycles per second.

The blade loadings utilized for the calibration of the strain-gage bridges were chordwise, vertical, actual, and torsional loadings, and several combinations of the last three. By using the results of the various loading conditions and the method of least squares, the strain-gage bridges were combined electrically to give a galvanometer deflection which best represented the known moment conditions. The sensitivity for both gage stations was thereby obtained in terms of moments per inch of galvanometer deflection.

TEST PROCEDURE, DATA REDUCTION, AND LIMITS OF ACCURACY

Test Procedure

Atmospheric turbulence.- Throughout the atmospheric-turbulence investigation the tests were conducted in a manner which would yield comparable data. In order to accomplish this end, the smooth-air and rough-air flights were made under conditions that were as nearly alike as possible, with the exception of the air turbulence.

The smooth- and rough-air tests were made in trim level flight at a constant rotor rotational speed with airspeeds ranging from 30 to 85 knots indicated airspeed. Cycles were chosen from each test to be analyzed harmonically for determination of the bending and torsional moments in the rotor blade.

Maneuvers.- In order to determine the effects of maneuvers, several types of moderate pull-ups were performed. Cyclic, collective, and combined cyclic-collective phased pull-ups were made at 60, 70, and 80 knots indicated airspeed. Cycles for the cyclic pull-ups were chosen to give information on the bending moments at the times marked by arrows on the time history shown in figure 3(a). For the collective pull-ups the cycles were chosen at the times shown in figure 3(b). In the combined pull-ups the cyclic stick was moved first, and the collective control movement followed in about $1\frac{1}{2}$ seconds. The analysis intervals for the combined pull-ups are shown in figure 3(c). Each analysis interval covers one revolution of the rotor blade.

Data Reduction

In order to determine the moments encountered by the rotor blade during the various flight conditions, two methods of data reduction were used. The two methods were (1) read-up of the peak-to-peak amplitude of the moment traces and (2) a 24-point harmonic analysis of the same traces.

In the first method, the vibratory bending moments were calculated by using one-half the peak-to-peak amplitude. The steady-state moments were determined by measuring the distance from the zero moment line to the midpoint of the trace peak-to-peak amplitude. This method of determining the steady-state moments does not take into consideration the harmonic content of the traces, but the results compare favorably with the steady-state moments obtained from the harmonic analyses. In order to determine the harmonic content of the moment traces, the second method of reducing the data was employed.

Limits of Accuracy

In determining the limit of accuracy, it was found that the largest errors are determined by the accuracy with which the oscillograph strain-gage records can be read. For this investigation the approximate reading error is ±0.01 inch. Based on reading error alone, the following limits of accuracy were obtained:

Flapwise bending moment at 40-percent-radius station, in-lb	±95
Flapwise bending moment at 14-percent-radius station, in-lb	±135
Chordwise bending moment at 14-percent-radius station, in-lb . . .	±225
Torsional moment at 14-percent-radius station, in-lb	±40

RESULTS AND DISCUSSION

In order to show the effect of atmospheric turbulence and moderate maneuvers on rotor-blade moments, records are presented and analyzed for various flight conditions. The increased moments due to atmospheric turbulence and moderate maneuvers are compared with the moments encountered in steady-flight conditions. The results of the harmonic analyses are analyzed in order to determine any possible resonant conditions.

Moment Records

Typical time histories of the blade bending and torsional moments are presented in figures 4 and 5. These figures show the chordwise bending moments and torsional moments measured on the blade at the 14-percent-radius station and the flapwise bending moments measured at both the 14- and the 40-percent-radius stations. (These moments are hereinafter referred to as 14-percent chordwise bending moments, 40-percent flapwise bending moments, and so forth.) The smooth- and rough-air comparison records shown in figure 4 represent the moments obtained during flight in smooth air and during flight in rough air in which the acceleration increment is less than 0.1g and between 0.1g and 0.2g. The moderate pull-up records shown in figure 5 represent the moments obtained during the intervals shown in figure 3 for the three types of maneuvers.

Examination of figure 4(a) shows the general character of the moment records obtained in forward flight at an indicated airspeed of 50 knots and with gust-produced acceleration increments of 0, 0.03g, and 0.1g. Most of the traces show a definite 1-per-revolution variation in combination with superposed higher harmonics. Slight changes in the harmonic content of the traces can be noted as the acceleration increases.

Figure 4(b) shows the same type of record obtained at an indicated airspeed of 85 knots and with gust-produced acceleration increments of 0, 0.04g, and 0.2g. The trends previously noted are also in evidence in this figure. The increased amplitude of the smooth-air trace, as compared with the amplitude of the smooth-air trace at 50 knots, is a result of the increased forward speed.

Figure 5 shows the moment records obtained during a cyclic, a collective, and a combined cyclic-collective pull-up maneuver. It can be seen that the general shape of each of the four traces is similar during all three maneuvers. During each of the maneuvers, each trace noticeably changes harmonic content and amplitude only at the maximum-acceleration point. As in the case of the smooth- and rough-air traces, the predominant variation is 1-per-revolution with higher harmonics superposed in varying amounts.

Maximum Vibratory Moments

The maximum vibratory and mean blade moments are shown in figures 6 and 7. Figure 6 shows the results for the smooth- and rough-air comparison, and figure 7 shows the results for the pull-up maneuvers.

Relationship between measured moments and blade life.- For the results presented herein, the maximum vibratory steady-flight moments are used as a base line for evaluating percentage increases in moments (which are shown to be a maximum of about 40 percent) due to gusts and control motions. In determining the significance of these percentage increases, it should be borne in mind that maximum vibratory moments about four times as large as the steady-state values herein have been determined in the analysis of some unpublished data on the same helicopter during other transient conditions. Thus, the increases due to gusts and control motions cannot determine whether or not these blades have infinite life; instead, their possible importance must be judged from a cumulative-fatigue standpoint in cases for which infinite life is not initially available.

Smooth- and rough-air comparison.- Figure 6 presents the maximum vibratory and mean moments plotted against the indicated airspeed for both smooth and rough air. An examination of the vibratory moments shows that there is no significant increase in the moments due to rough air at indicated airspeeds up to about 50 knots. At 70 knots there are no large increases in the rough-air moments except for the 14-percent flapwise bending moments. The rough-air moments at 85 knots show increases over the smooth-air moments ranging from approximately 10 percent to 40 percent. The acceleration increment at this speed was 0.2g. An inspection of the mean moments in figure 6 shows that the steady-state values tend to remain fairly constant throughout the speed range. The increases in these moments due to rough air at 85 knots range from approximately 20 percent to 45 percent in this case. In all cases, the increased moments due to gusts were accompanied by center-of-gravity accelerations.

Moderate maneuvers.- Figure 7 is a time-history presentation of stick position, acceleration, and maximum vibratory and mean moments obtained during the three types of maneuvers. Figure 7(a) shows a cyclic pull-up at about 70 knots; figure 7(b) shows a collective pull-up at about 80 knots; figure 7(c) shows a combined cyclic-collective pull-up at about 70 knots. In all three maneuvers, zero time is taken as the point at which the pull-up is initiated. The maximum acceleration increments reached in these pull-ups range from 0.2g to 0.4g.

An examination of the three maneuvers shows that the 14-percent flapwise bending and 14-percent torsional moments seem to be the most affected by the pull-ups. The average increase for the total flapwise bending moments at the 14-percent station during the pull-ups was found to be about 30 percent; the total torsional moments at the same station averaged an increase of about 50 percent. The 40-percent flapwise and 14-percent chordwise total bending moments both had an average increase of only 10 percent during the three pull-ups.

Harmonic Analysis of Moment Records

In order to determine the harmonic content of the moment records, it was decided to analyze parts of these records harmonically. As an aid in interpreting the harmonic analyses of the moment records, it was necessary to obtain a resonance diagram of the variation of the natural blade bending frequency with rotor speed to determine whether resonance amplification was responsible for some of the increased moments. This diagram (fig. 8) was determined by using the procedure of reference 5 and the measured nonrotating-blade frequencies. An inspection of the figure reveals possible resonant amplification of the second and third bending modes in the normal operating range. The experimentally determined nonrotating shapes of the first three modes are also shown in the upper left-hand corner of the figure. It can be seen from this insert that the two radial stations chosen for this investigation will respond very well to all three of these mode shapes.

The results of the harmonic analyses are shown in figures 9 to 12 in which are plotted the steady-state and the first 10 harmonic moments. Although the magnitudes of some of the higher harmonics are below the limits of accuracy, they have nevertheless been included. In all plots, a positive steady-state value indicates (1) for flapwise bending moment, compression in the upper surface of the blade, (2) for chordwise bending moment, compression in the trailing edge of the blade, and (3) for torsional moment, couple tending to rotate the blade nose upward. The steady-state values of the chordwise bending and torsional moments were found to be negative in all cases as is shown by minus signs over the bar graphs.

Smooth- and rough-air comparisons.- The results of the effects of atmospheric turbulence on the rotor-blade moments are shown in figure 9. The bar graphs present the effects of rough air as compared with the effects of smooth air. In order to help illustrate the results, the rough-air condition is divided into two categories: (1) turbulence that caused an acceleration increment of less than 0.1g and (2) turbulence that caused an acceleration increment between 0.1g and 0.2g. For the three speeds presented, the turbulence which falls in the second category resulted in acceleration increments of 0.1g for the 50-knot test, 0.15g for the 70-knot test, and 0.2g for the 85-knot test.

An inspection of figure 9, and also of figure 6, reveals that gust-produced acceleration increments of less than 0.1g produce little or no additional periodic blade moments that would be significant to fatigue calculations. These same figures show that gust-produced acceleration increments of 0.1g and 0.15g obtained in the 50-knot and 70-knot tests, respectively, also produce little increase in the periodic blade moments except for the higher harmonics at the 14-percent flapwise bending station. The gust-produced acceleration increment of 0.2g, obtained in the 85-knot test, was found to produce appreciably increased periodic moments. This increased response to gusts at the higher speeds may possibly cause critical effects in future high-speed helicopters. In general, a trend toward increased higher harmonics due to increased acceleration increments is in evidence. The increased higher harmonic moments may be of some interest in other connections such as excessive vibration and its resultant passenger discomfort.

In order to determine whether these increased moments could have an effect on the fatigue life for current helicopters of the same general type, a check of the time spent in this acceleration condition was made. A check of some unpublished data for airmail operations revealed that the commercial version of the helicopter used in this investigation encountered turbulence which caused acceleration increments that ranged from barely perceptible to 0.1g only about 6 percent of the total time and encountered turbulence that caused an acceleration increment between 0.1 and 0.2g during less than 1 percent of the total flying time. Turbulence that caused an acceleration increment between 0.1 and 0.2g was encountered during the present investigation for about 6 percent of the total flying time. A check of reference 6 revealed that the total time spent at or above a positive acceleration increment of 0.15g was only 0.4 percent of the total operating time for the airmail operations reported therein. Reference 1 showed that an average of about 3.5 flights was required to produce an acceleration increment that is greater than that reported herein, that is, 0.2g. Since the moments imposed by gust-produced acceleration increments of 0.15g and below are very slight, they can be considered of little consequence in calculating the contribution to fatigue life of the principal part of the flying time. The increased moments resulting from gust-produced acceleration increments of over 0.15g are not to be considered directly in connection with the primary purpose of this report and have been presented to help bracket the results and to provide some preliminary ideas regarding atmospheric turbulence that is more severe than that encountered during the principal part of the flying time.

Moderate maneuvers.- The effects of moderate pull-up maneuvers are shown in figures 10 to 12. The results are presented for cyclic, collective, and combined cyclic-collective pull-up maneuvers. The maximum acceleration increments reached in these pull-ups range from 0.2g to 0.4g.

An inspection of figures 10 to 12, and also of figure 7, reveals that some increased moments in the rotor blades can be expected at the maximum-acceleration point. Again, the tendency toward increased higher harmonics can be noted at the higher acceleration levels. Particularly noticeable is the increase in flapwise bending moments for harmonics such as the fifth and the eighth. The increased moments for these harmonics are probably caused by the near resonant condition as the rotational speed increases during the maneuver. Some of the large increases in the torsional moments at the higher speeds and higher acceleration increments are believed to be caused in part by rotor-blade stall. Since these increased moments are all produced by acceleration increments that are greater than 0.15g, the results at the maximum acceleration point for these maneuvers do not directly indicate the results for the principal part of the flying time.

The control displacements used were intentionally made larger and more rapid than those which would occur during the principal part of the flying time and were held much longer than the vast majority of displacements made in normal operations. Acceleration increments two or three times as high as the value of 0.15g referred to were thus obtained. The moments for these exaggerated conditions show only moderate increases (in terms of the margin between the steady-flight-condition moments and the maximum transient moments the blades could stand). Since these moderate increases show up as increased higher harmonic moments, they may be of interest as far as vibration and comfort level are concerned and as an indication of what to expect with still more severe conditions. Experience, as well as logic, has shown that smaller displacements and lower acceleration increments would produce even smaller moment changes; the values used, therefore, serve to bracket the possible values for 0.15g increment maneuvers and hence for 99 percent of the flying time.

The portions of the maneuvers most indicative of the results, obtained during the principal part of the flying time, would be during the initial control movement for the collective and combined pull-ups and at the acceleration flat spot for the cyclic pull-ups. An inspection of these portions in figures 10 to 12 reveals that there is little or no increase in the moments encountered. Therefore, the periodic moments due to moderate control motions encountered during normal operations will not be significant for calculating fatigue life during the bulk of the flying time.

Applicability of NACA Helicopter VGHN Recorder Surveys

The results of the present investigation show that both gusts and control motions, for the range of severities of most concern (that is, $\Delta a_n < 0.15g$), had little effect on the rotor-blade periodic moments. Since this range of severities includes more than 99 percent of the flying time, the NACA helicopter VGHN recorder indications of flight conditions in combination with prototype strain data, for these classifiable conditions, can be used to determine the cumulative fatigue effects. The remaining fraction of 1 percent of the flying time involves intermediate to severe transient conditions. Some of the intermediate transient conditions are used in this study to help bracket the results that can be expected during the principal part of the flying time. The severe transient conditions are not covered in the present study. However, it is believed from preliminary study of the problem that further investigation may show that it is also possible to treat these intermediate and severe conditions by the use of NACA helicopter VGHN recorder surveys in combination with prototype strain measurements.

CONCLUSIONS

An investigation of the effects of atmospheric turbulence and moderate maneuvers on the periodic rotor blade moments of a medium-size, fully articulated, single-rotor helicopter in the speed range of 30 to 90 knots indicates the following conclusions:

1. Atmospheric turbulence which caused a center-of-gravity acceleration increment of less than 0.15g (where g is the acceleration due to gravity) had little effect on the rotor blade moments. Turbulence which caused a center-of-gravity acceleration increment between 0.15g and 0.2g produced some increase in individual harmonics of the moments, especially for the higher harmonics. These increased moments, which are small in relation to the margin between the smooth-air moments and the maximum moments encountered, are applied for a small percentage of the total flying time and, therefore, are considered of little consequence in regard to that part of the cumulative fatigue analysis that covers the principal part of the flying time.

2. Moderate maneuvers, which produced center-of-gravity acceleration increments of less than 0.15g, also had little effect on the rotor blade moments. Maneuvers which produced center-of-gravity acceleration increments of more than 0.15g were found to produce increased moments for some of the individual harmonics with more emphasis being placed on the higher harmonics. As in the case with atmospheric turbulence, these increased moments, applied for a small percentage of the total flying time, are small in relation to the margin between the smooth-air moments and the maximum moments encountered and are of little consequence in regard to cumulative-fatigue-damage calculations covering the principal part of the flying time.

3. Since atmospheric turbulence and moderate maneuvers do not unduly affect rotor blade moments except when accompanied by center-of-gravity accelerations during the principal part of the flying time, the time spent in various flight conditions, as determined by an NACA helicopter

VGHN recorder, can be safely used for a large part of the fatigue-life determination.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 25, 1957.

REFERENCES

1. Hazen, Marlin E.: A Study of Normal Accelerations and Operating Conditions Experienced by Helicopters in Commercial and Military Operations. NACA TN 3434, 1955.

2. Jewel, Joseph W., Jr., and Carpenter, Paul J.: A Preliminary Investigation of the Effects of Gusty Air on Helicopter-Blade Bending Moments. NACA TN 3074, 1954.

3. Maglieri, Domenic J., and Reisert, Thomas D.: Gust-Tunnel Investigation of the Effect of a Sharp-Edge Gust on the Flapwise Blade Bending Moments of a Model Helicopter Rotor. NACA TN 3470, 1955.

4. Crim, Almer D.: Gust Experience of a Helicopter and an Airplane in Formation Flight. NACA TN 3354, 1954.

5. Yntema, Robert T.: Simplified Procedures and Charts for the Rapid Estimation of Bending Frequencies of Rotating Beams. NACA TN 3459, 1955. (Supersedes NACA RM L54G02.)

6. Crim, Almer D., and Hazen, Marlin E.: Normal Accelerations and Operating Conditions Encountered by a Helicopter in Air-Mail Operations. NACA TN 2714, 1952.

TABLE I

PRINCIPAL DIMENSIONS AND APPROXIMATE PHYSICAL

CHARACTERISTICS OF TEST HELICOPTER

Gross weight, lb	6,900
Number of blades	3
Rotor blade radius, ft	26.5
Flapping-hinge offset, ft	0.75
Weight of blades (approximate), lb/blade	136
Main rotor blade:	
Type	All metal, constant chord
Twist, deg	-8
Airfoil section	NACA 0012
Blade chord, ft	1.368
Rotor solidity, σ	0.0493
Approximate rotor-blade mass constant, γ	11
Rotor blade tip speed, ft/sec	538
Disk loading, lb/sq ft	3.12
Rotor angular velocity, radians/sec	20.3
Center of gravity, inches from reference datum (reference datum 14.5 in. forward of nose)	129.6

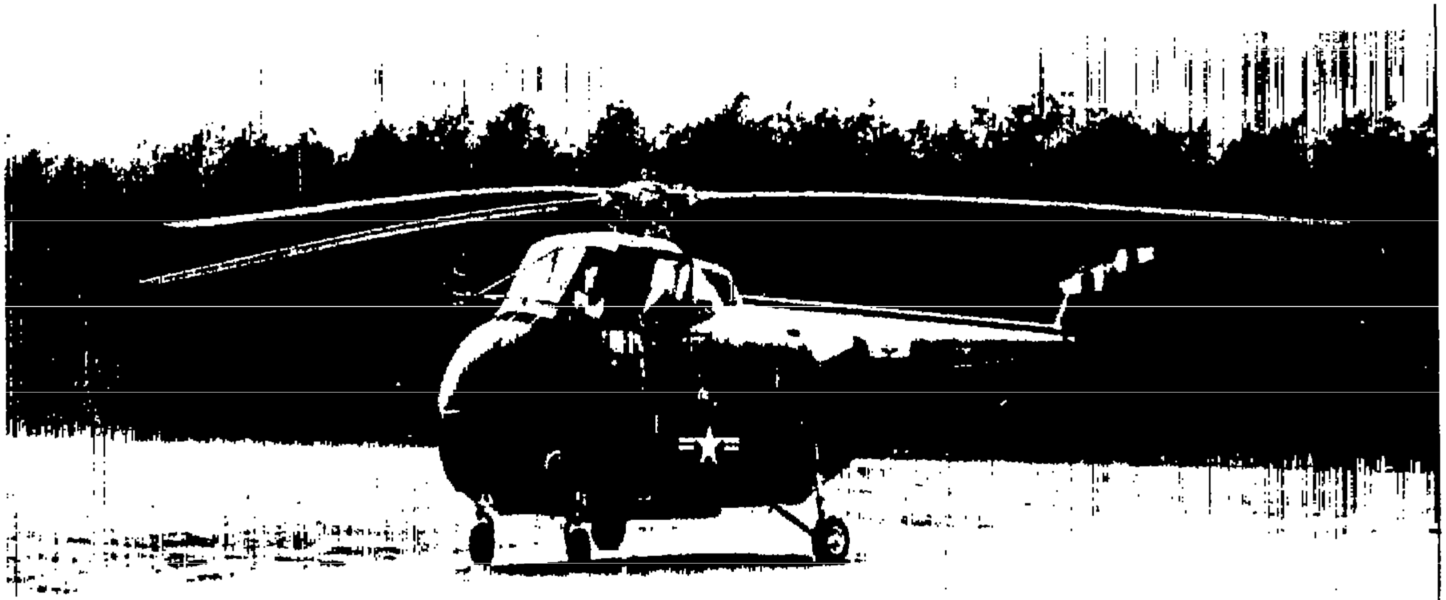


Figure 1.- Test helicopter. L-84196

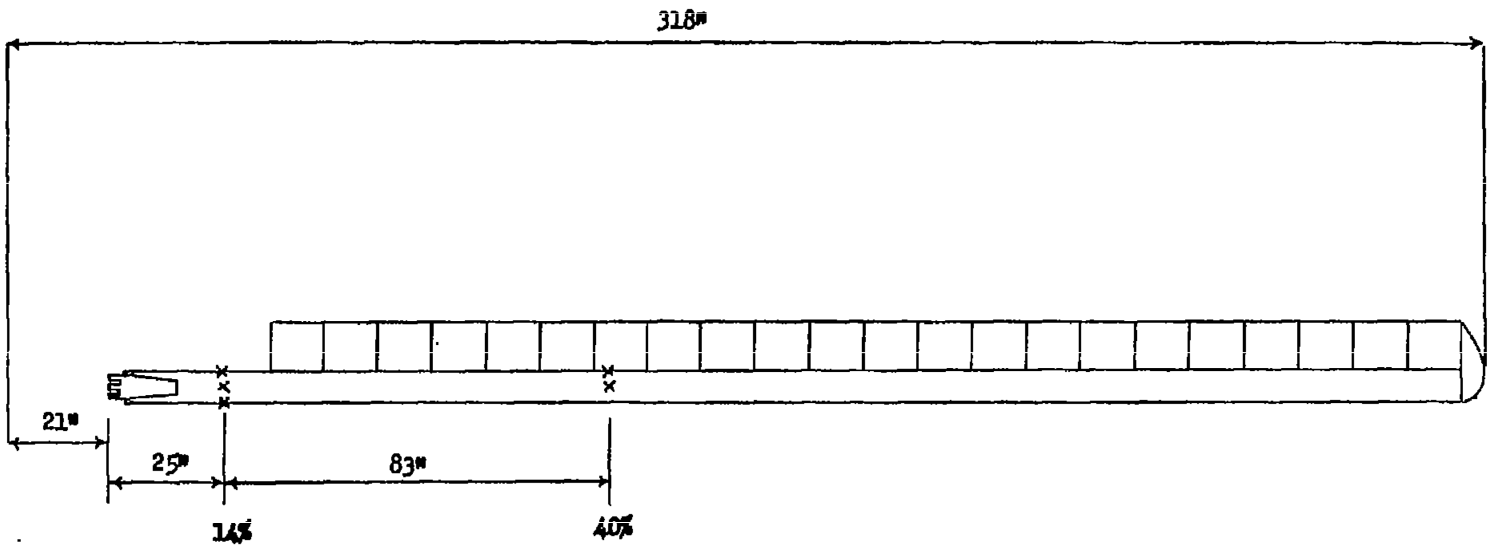
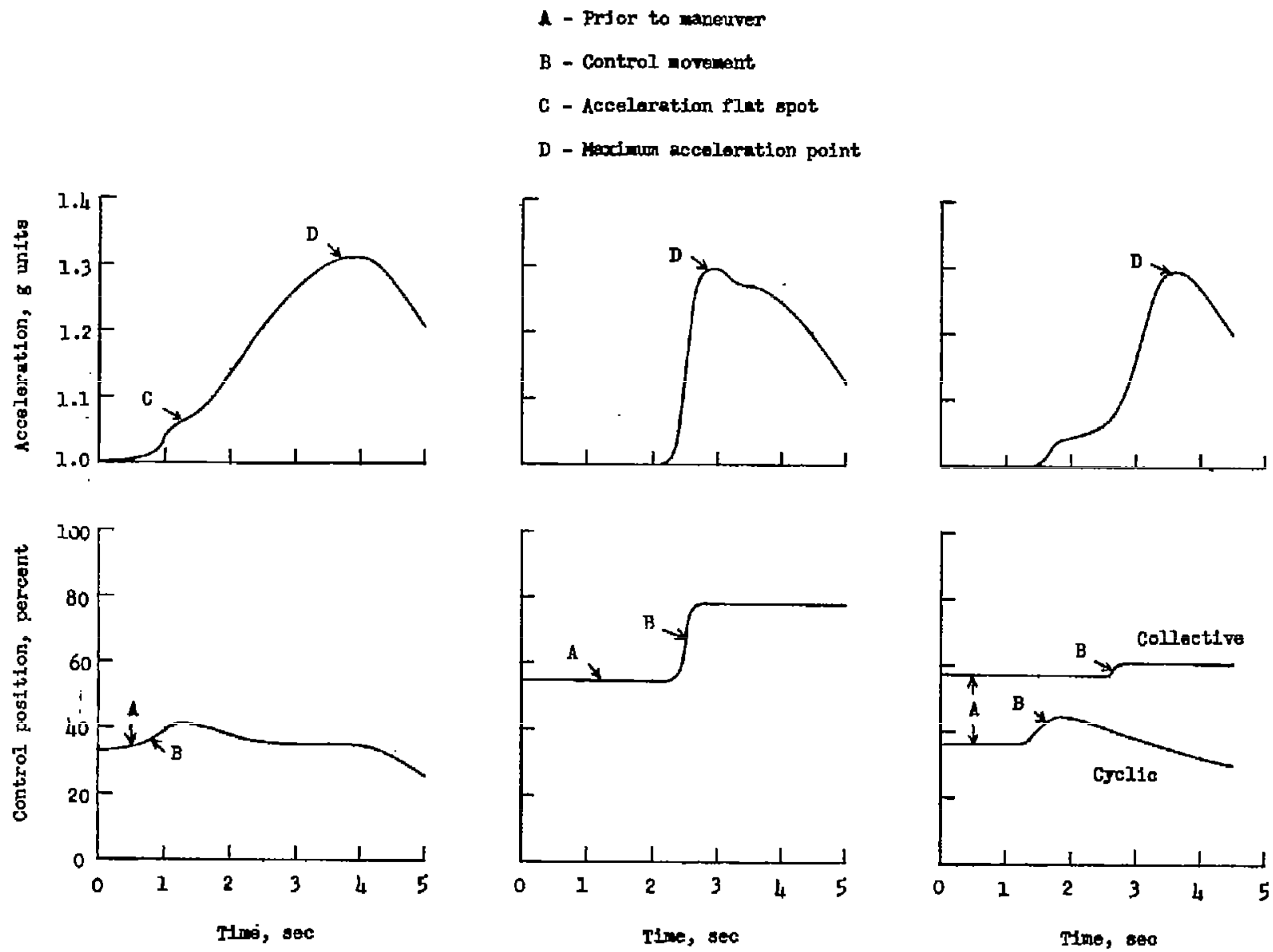


Figure 2.- Strain-gage installation.

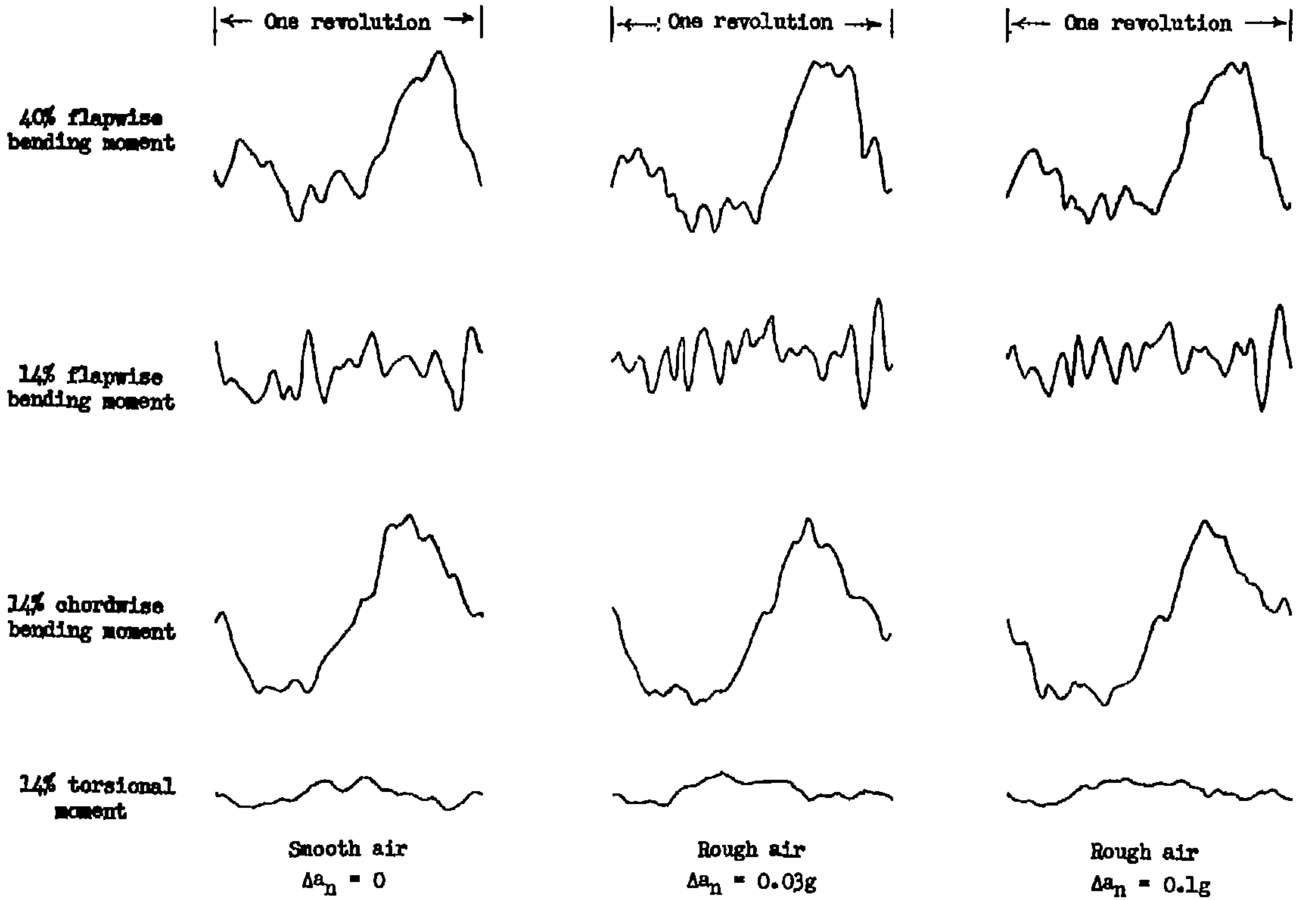


(a) Cyclic pull-ups.

(b) Collective pull-ups.

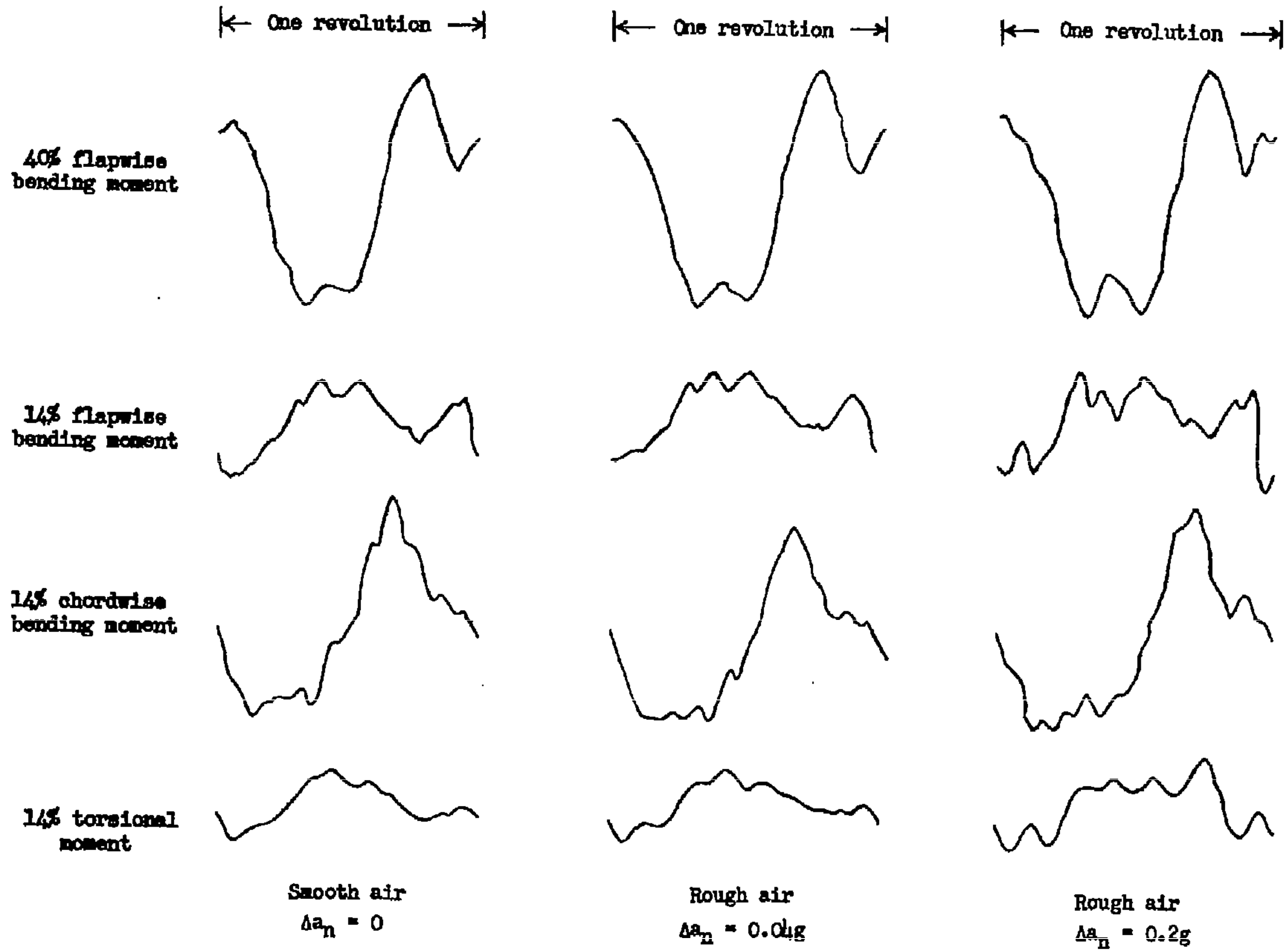
(c) Combined pull-ups.

Figure 3.- Typical time histories of acceleration and control position during cyclic, collective, and combined pull-up maneuvers.



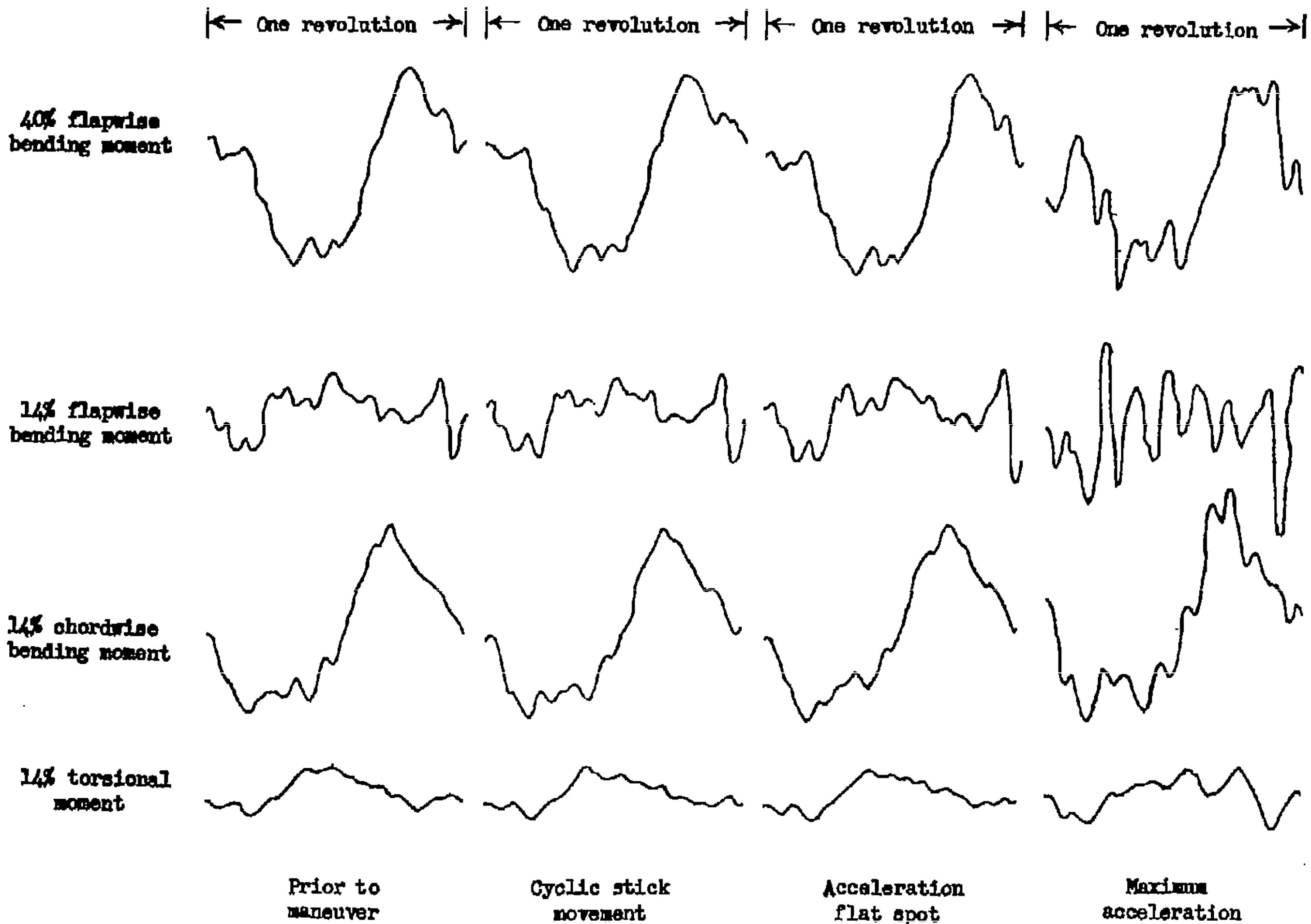
(a) $V_i = 50$ knots.

Figure 4.- Typical time histories of blade bending and torsional moments during smooth- and rough-air flights at 50 and 85 knots.



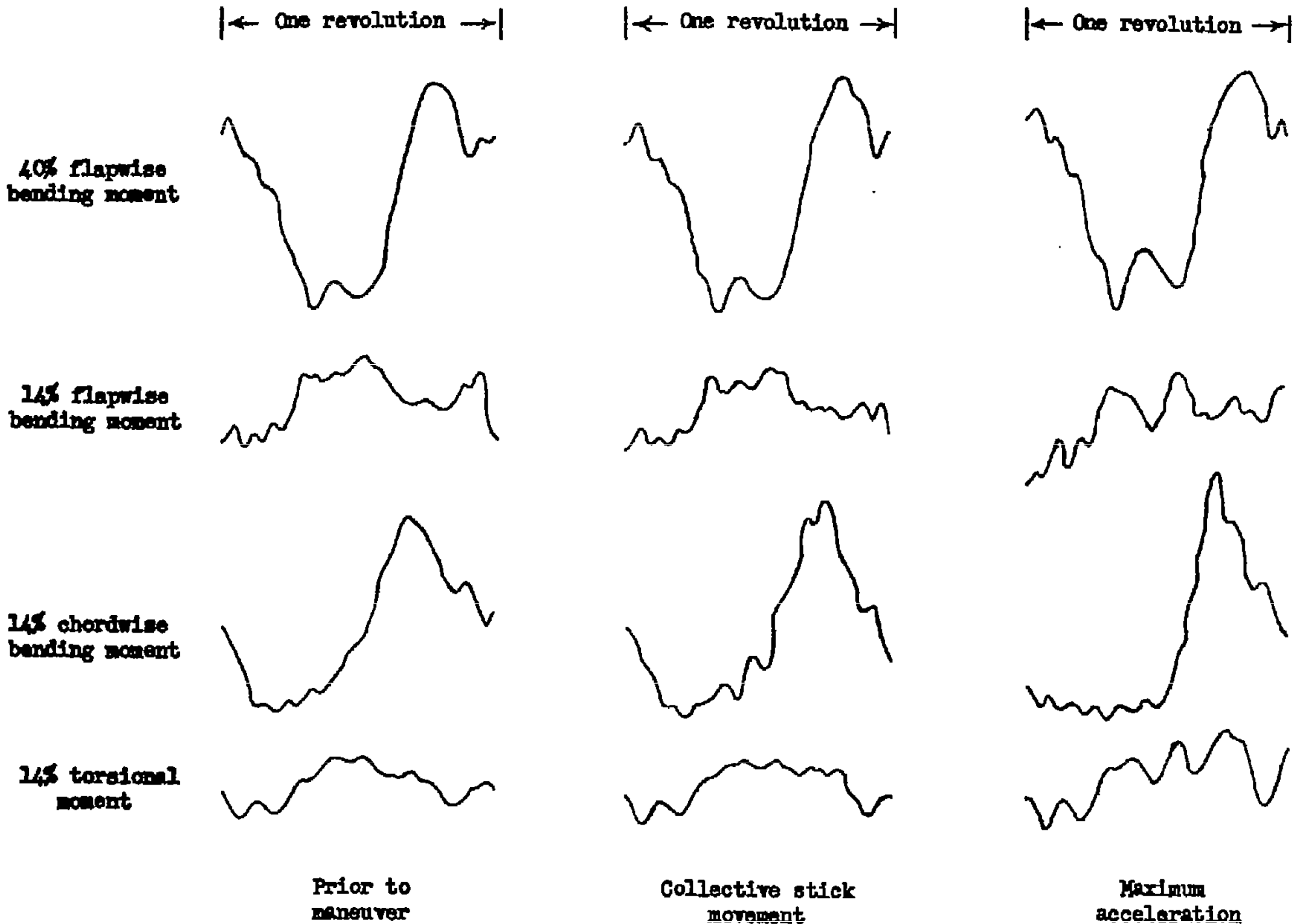
(b) $V_i = 85$ knots.

Figure 4.- Concluded.



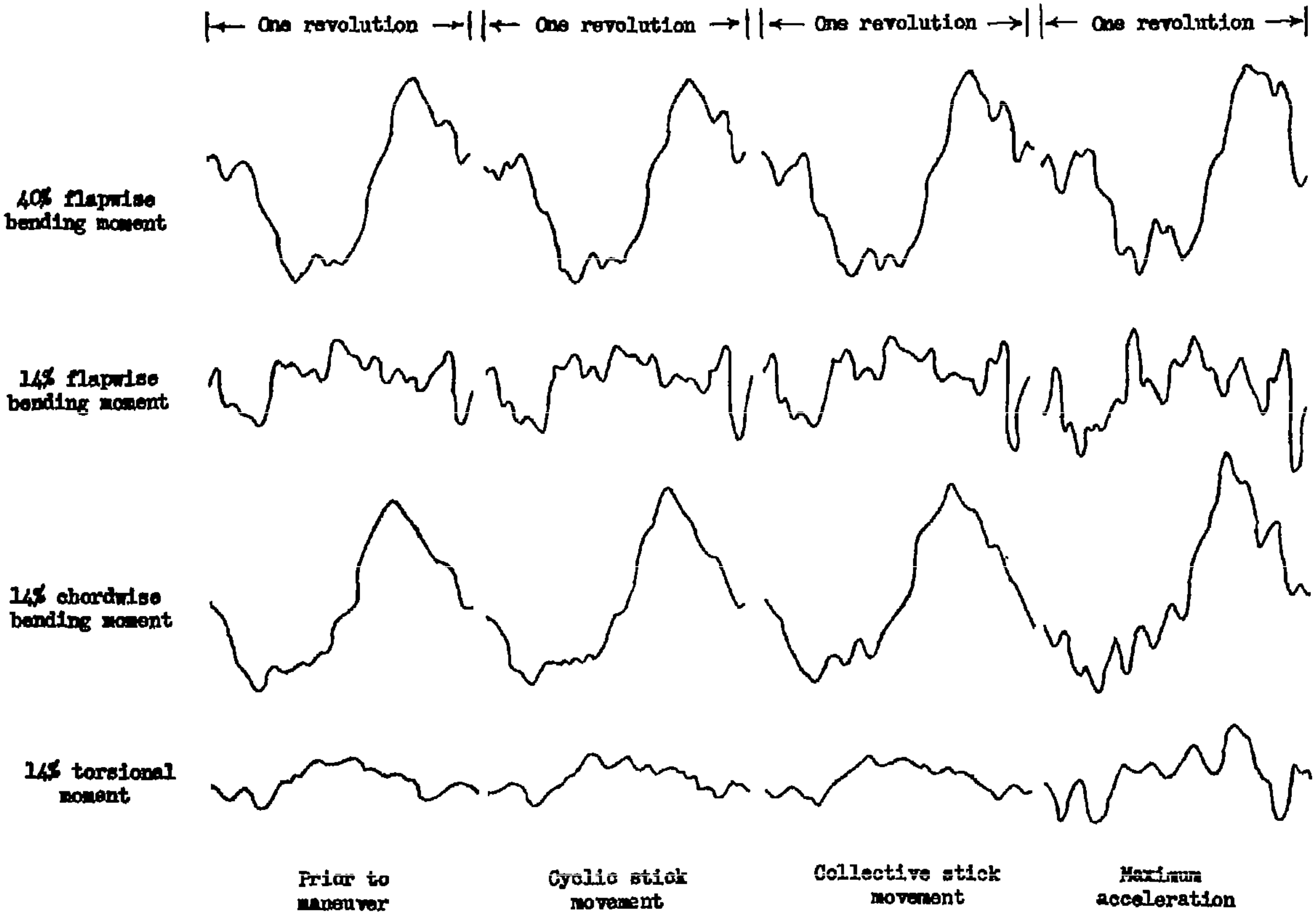
(a) Cyclic pull-ups.

Figure 5.- Typical time histories of blade bending and torsional moments during moderate cyclic, collective, and combined cyclic-collective pull-up maneuvers at the intervals shown in figure 3.



(b) Collective pull-ups.

Figure 5.- Continued.



(c) Combined pull-ups.

Figure 5.- Concluded.

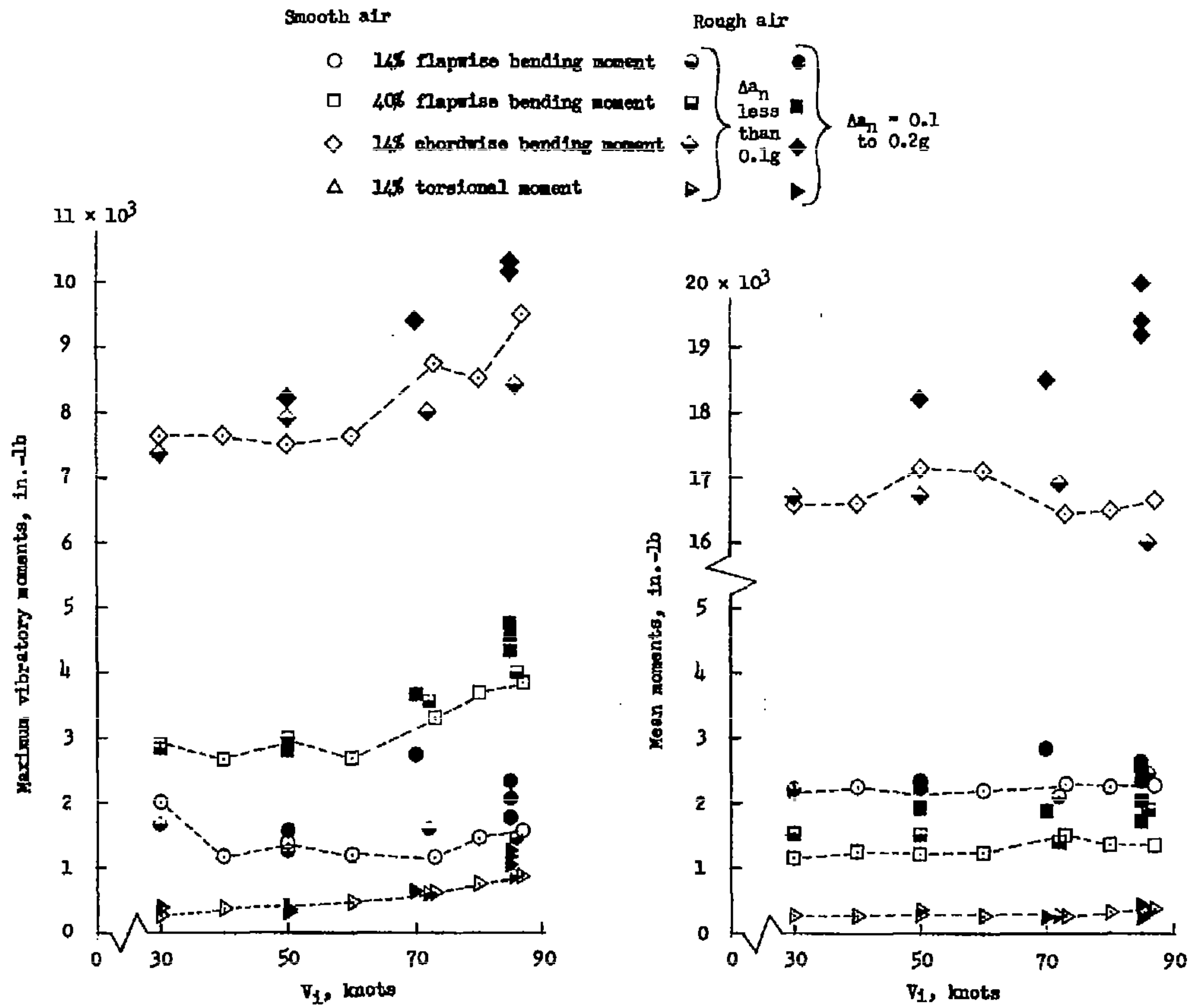
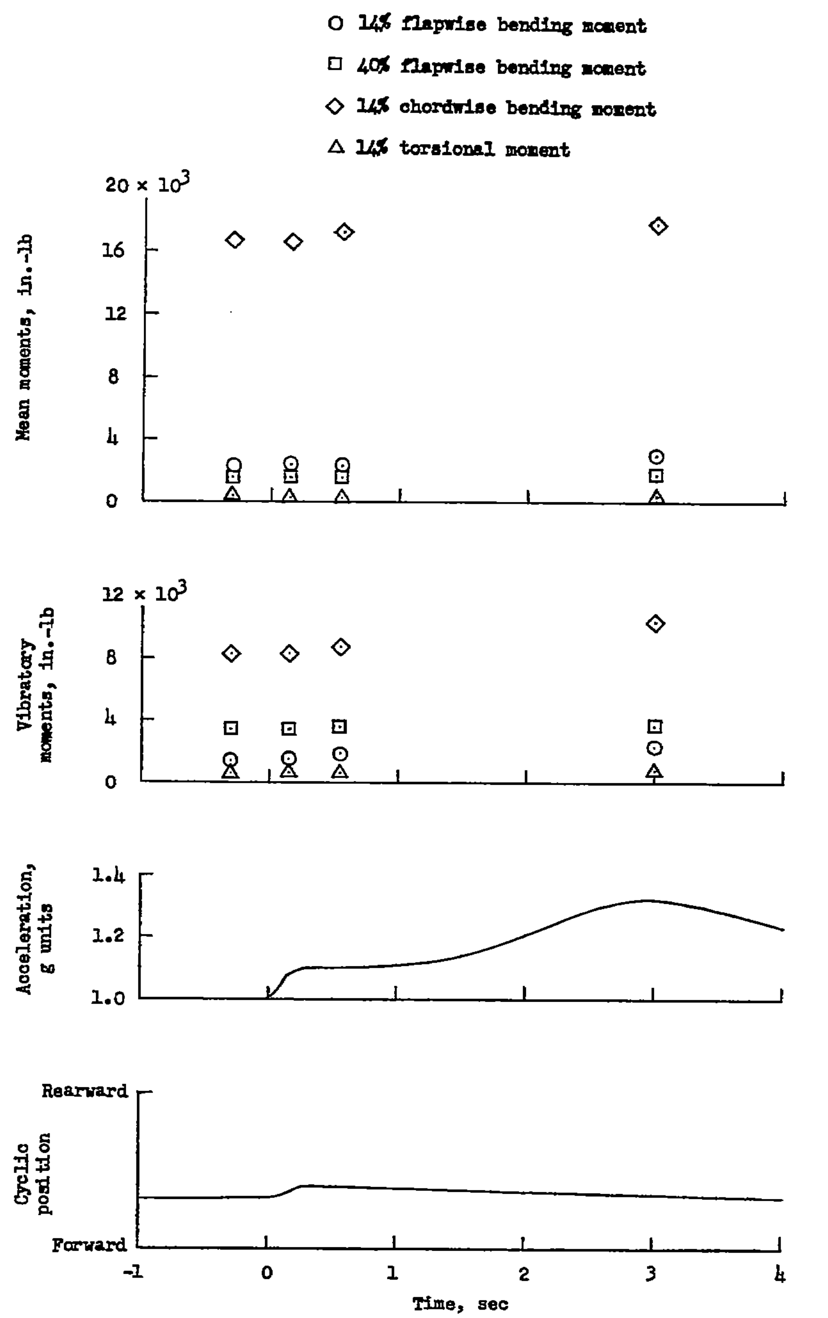
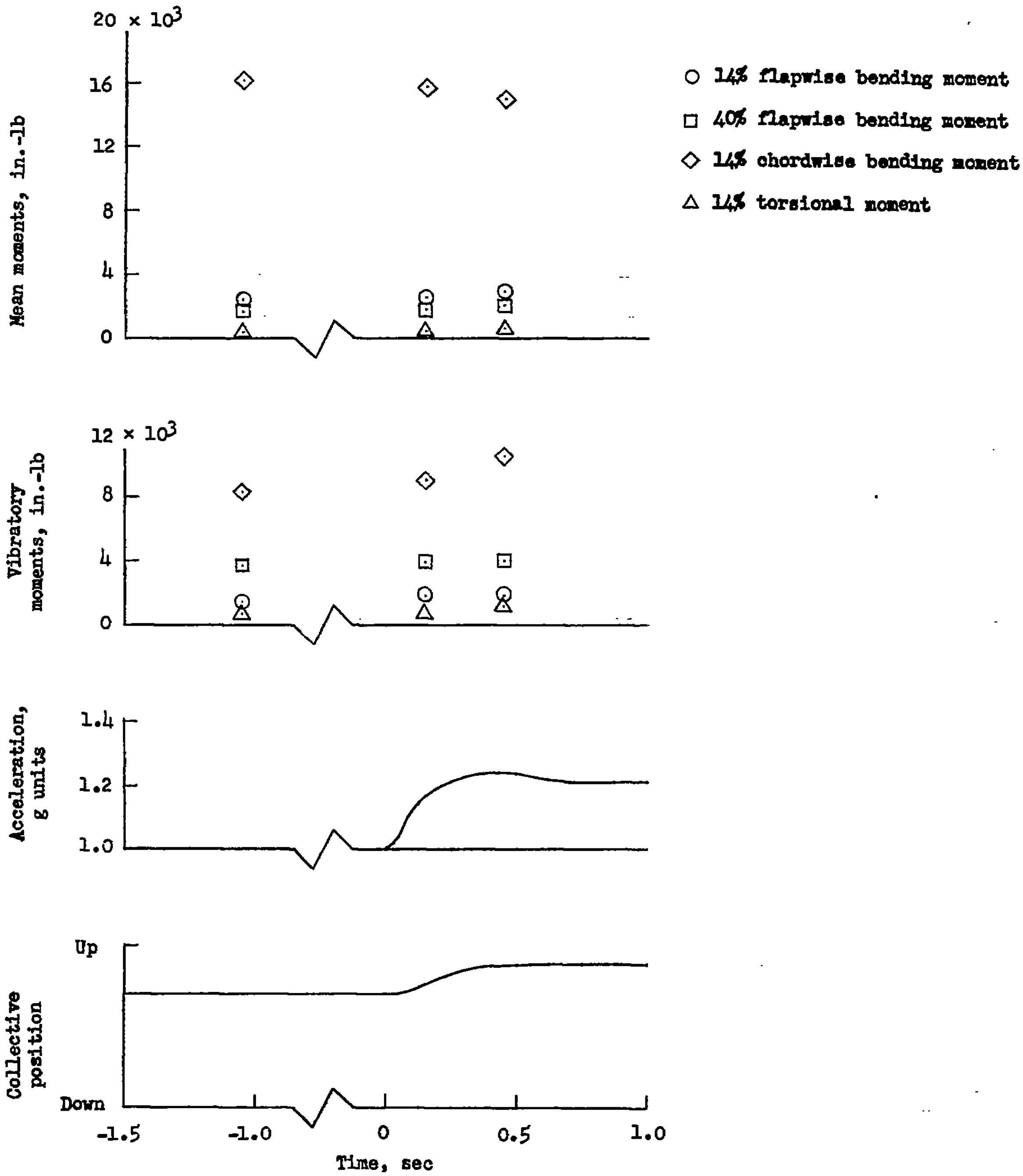


Figure 6.- Maximum vibratory and mean moments plotted against indicated airspeed during smooth and rough air.



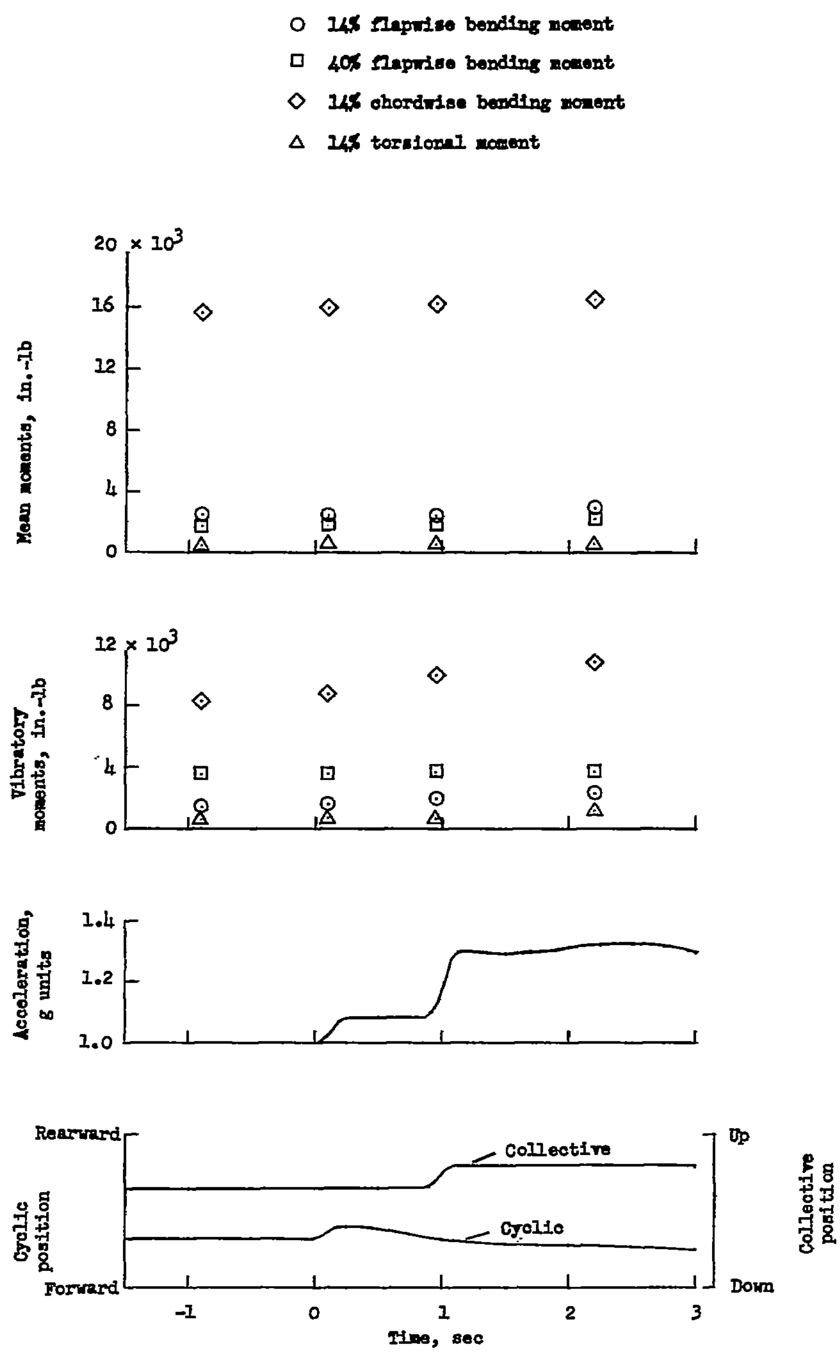
(a) Cyclic pull-ups; V_i = 70 knots.

Figure 7.- Typical time histories of vibratory and mean moments, acceleration, and stick position for cyclic, collective, and combined pull-up maneuvers.



(b) Collective pull-ups; V_i = 80 knots.

Figure 7.- Continued.



(c) Combined cyclic-collective pull-ups; V_i = 70 knots.

Figure 7.- Concluded.

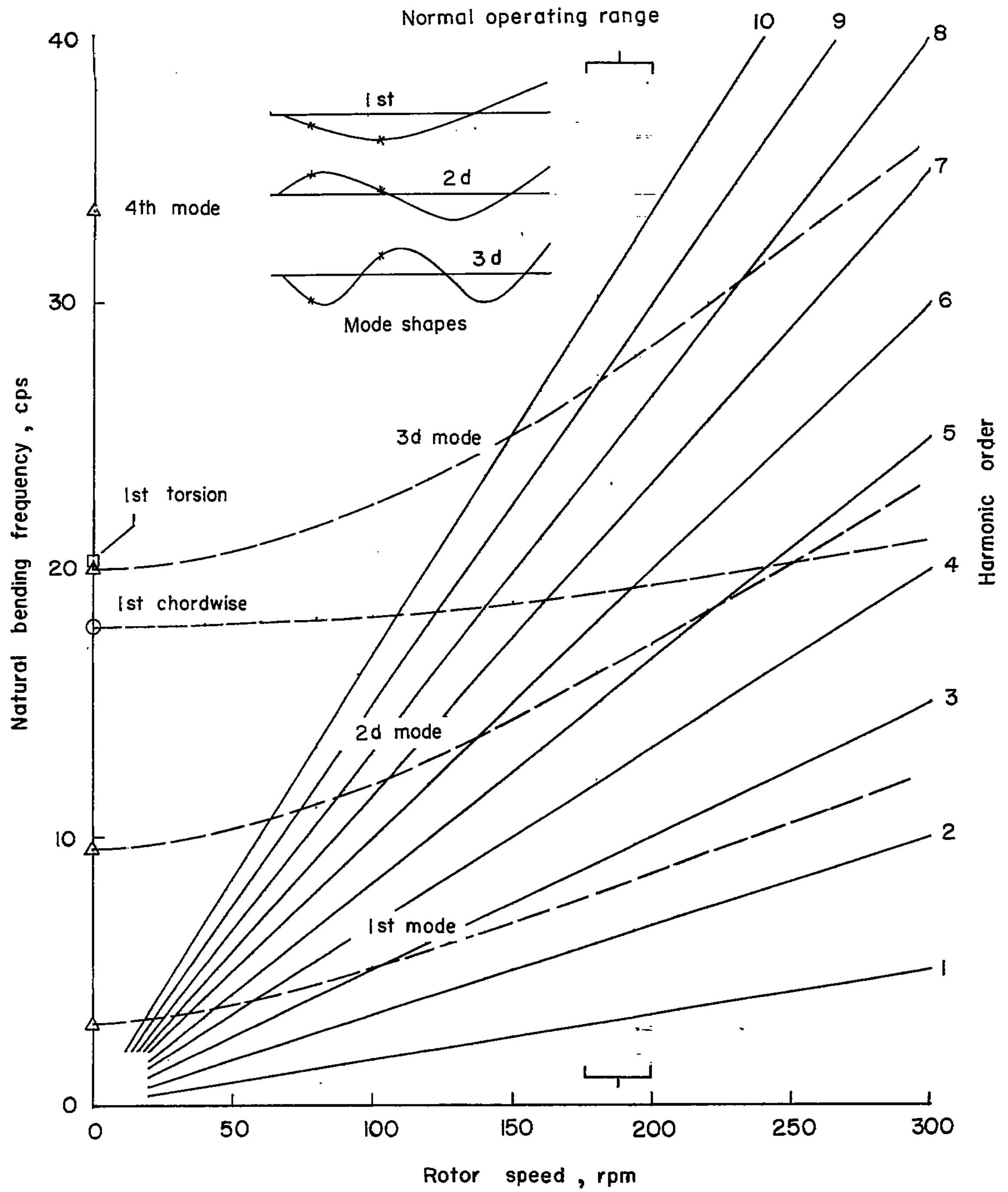


Figure 8.- Rotor blade resonance diagram.

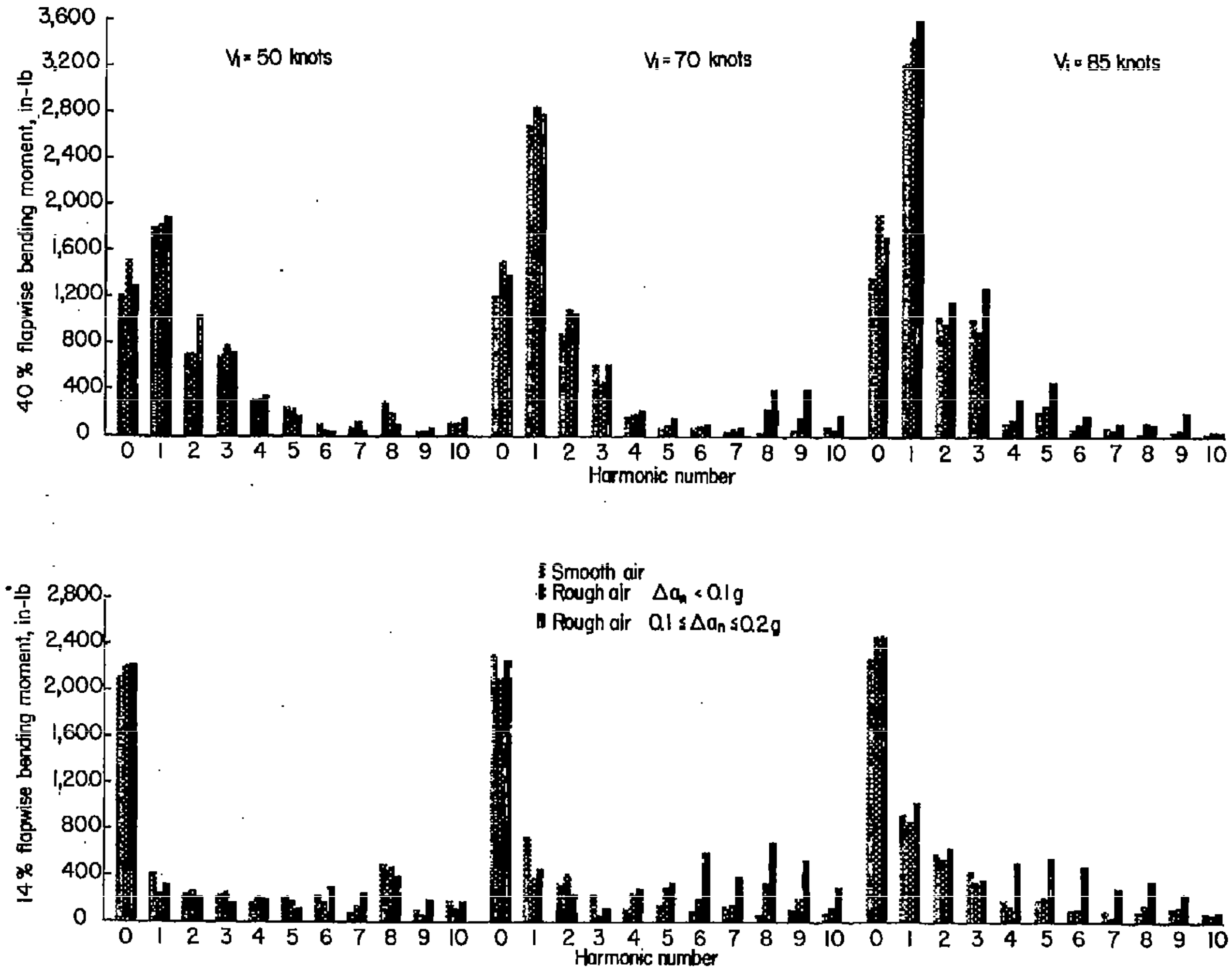


Figure 9.- Atmospheric turbulence effects on rotor blade moments at various forward speeds.

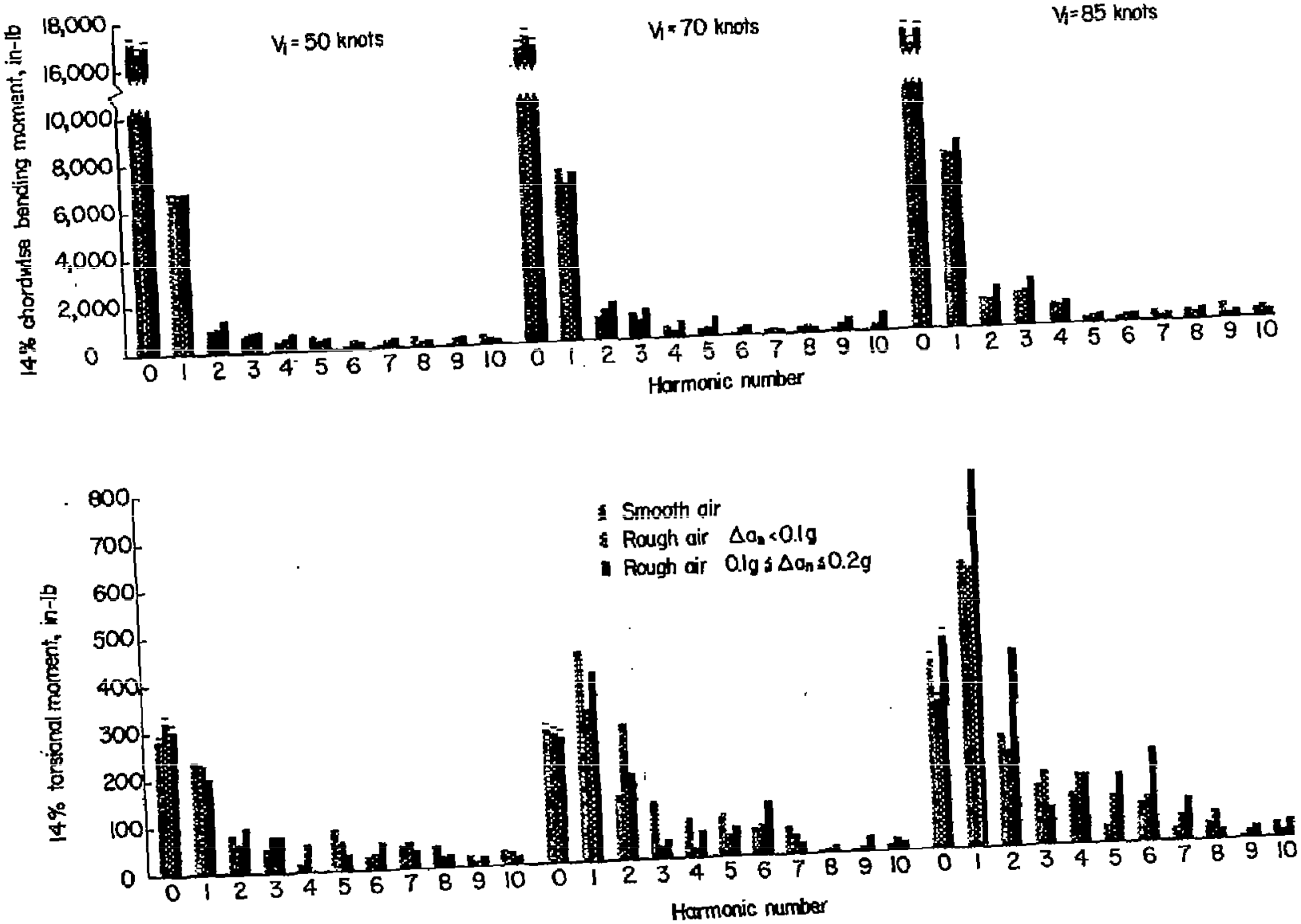


Figure 9.- Concluded.

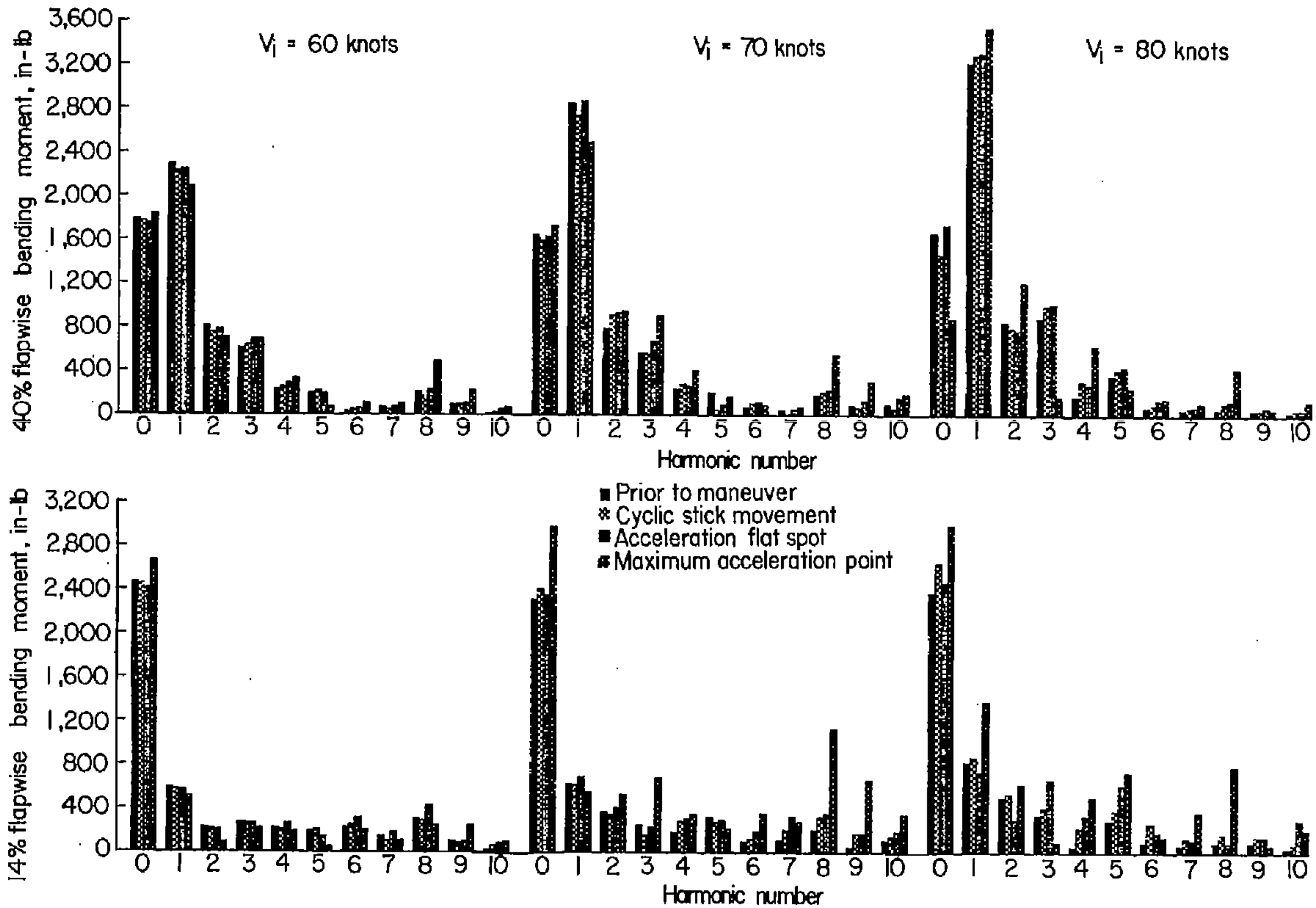


Figure 10.- Effects of moderate cyclic pull-up maneuvers on rotor blade moments at various forward speeds.

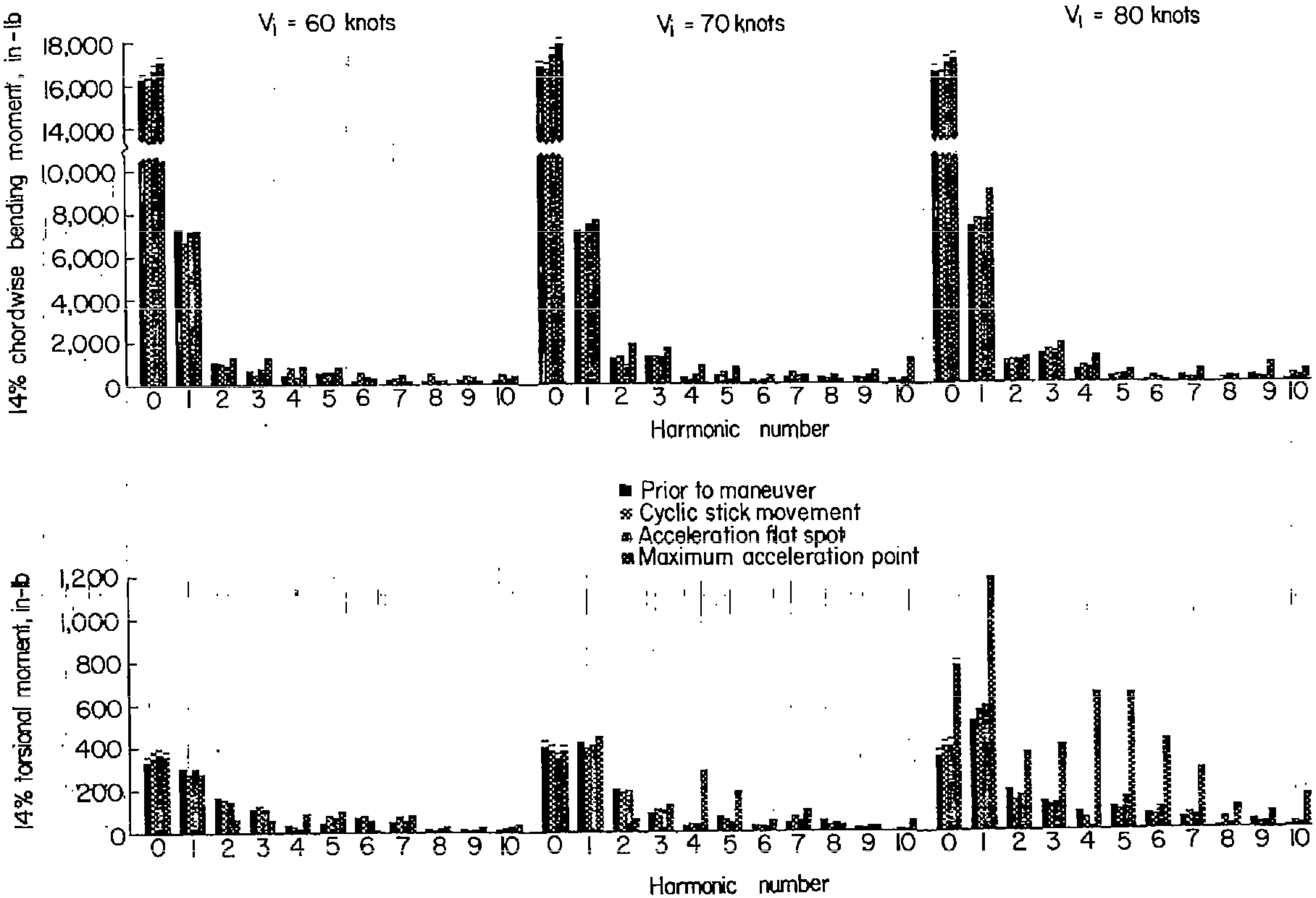


Figure 10.- Concluded.

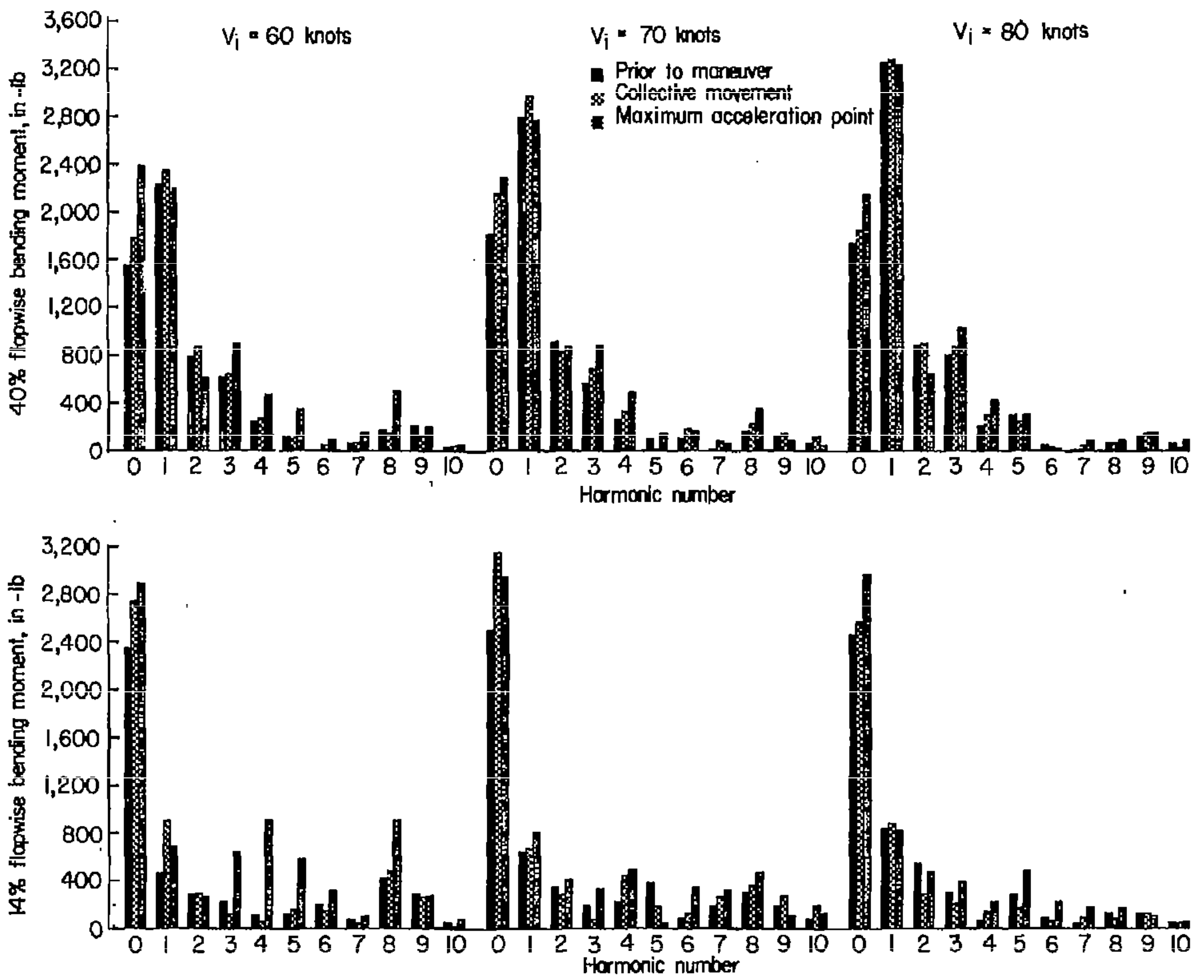


Figure 11.- Effects of moderate collective pull-up maneuvers on rotor blade moments at various forward speeds.

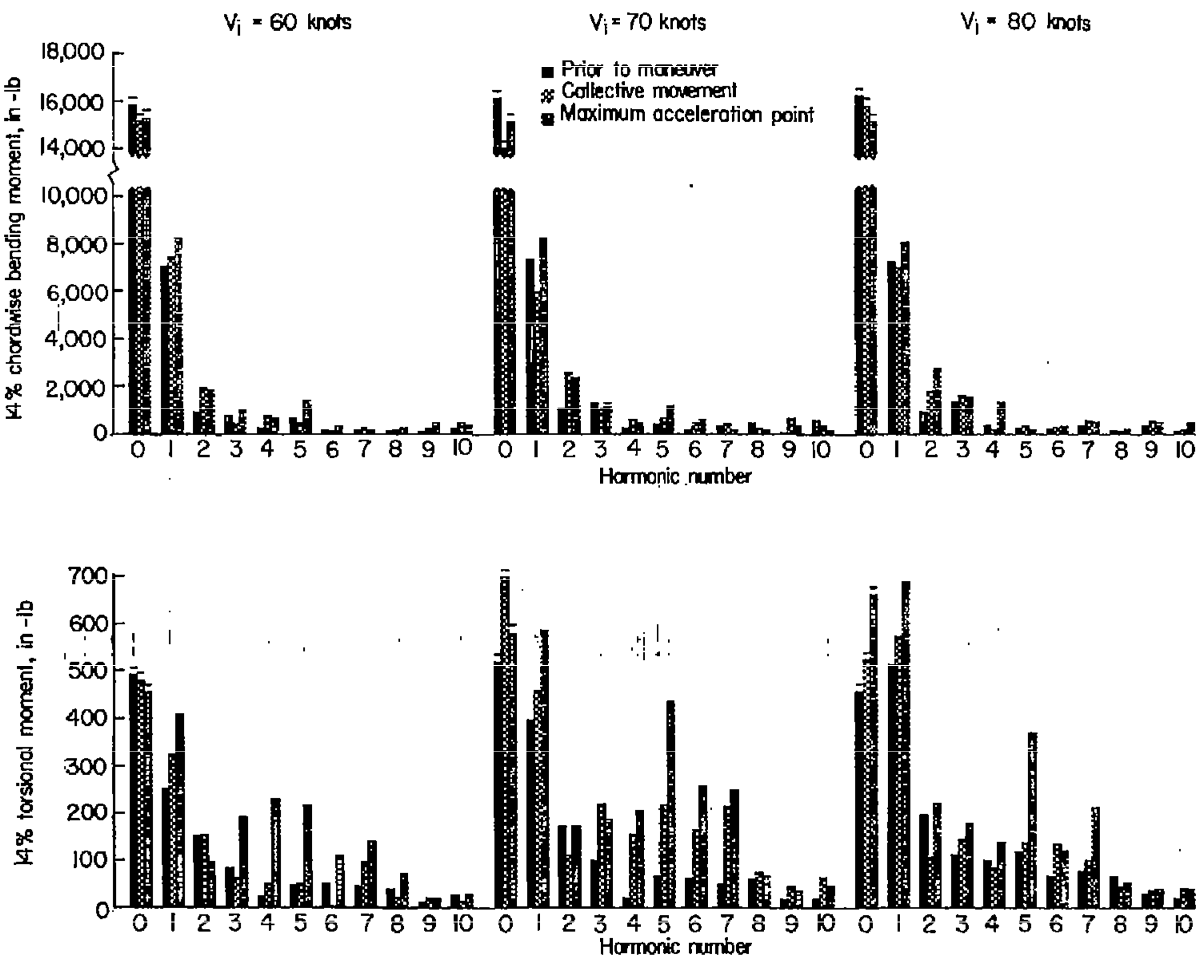


Figure 11.- Concluded.

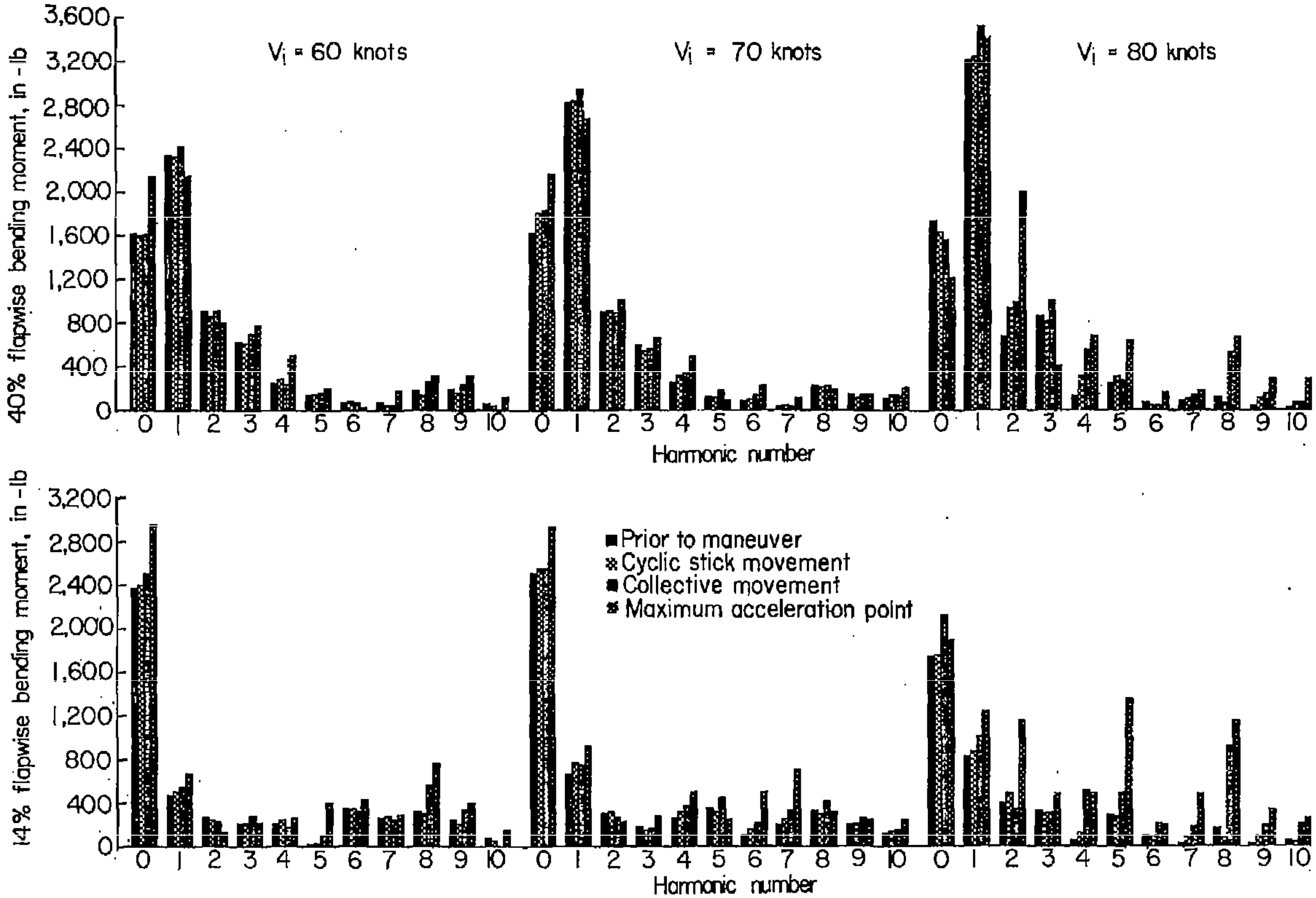


Figure 12.- Effects of moderate combined pull-up maneuvers on rotor blade moments at various forward speeds.

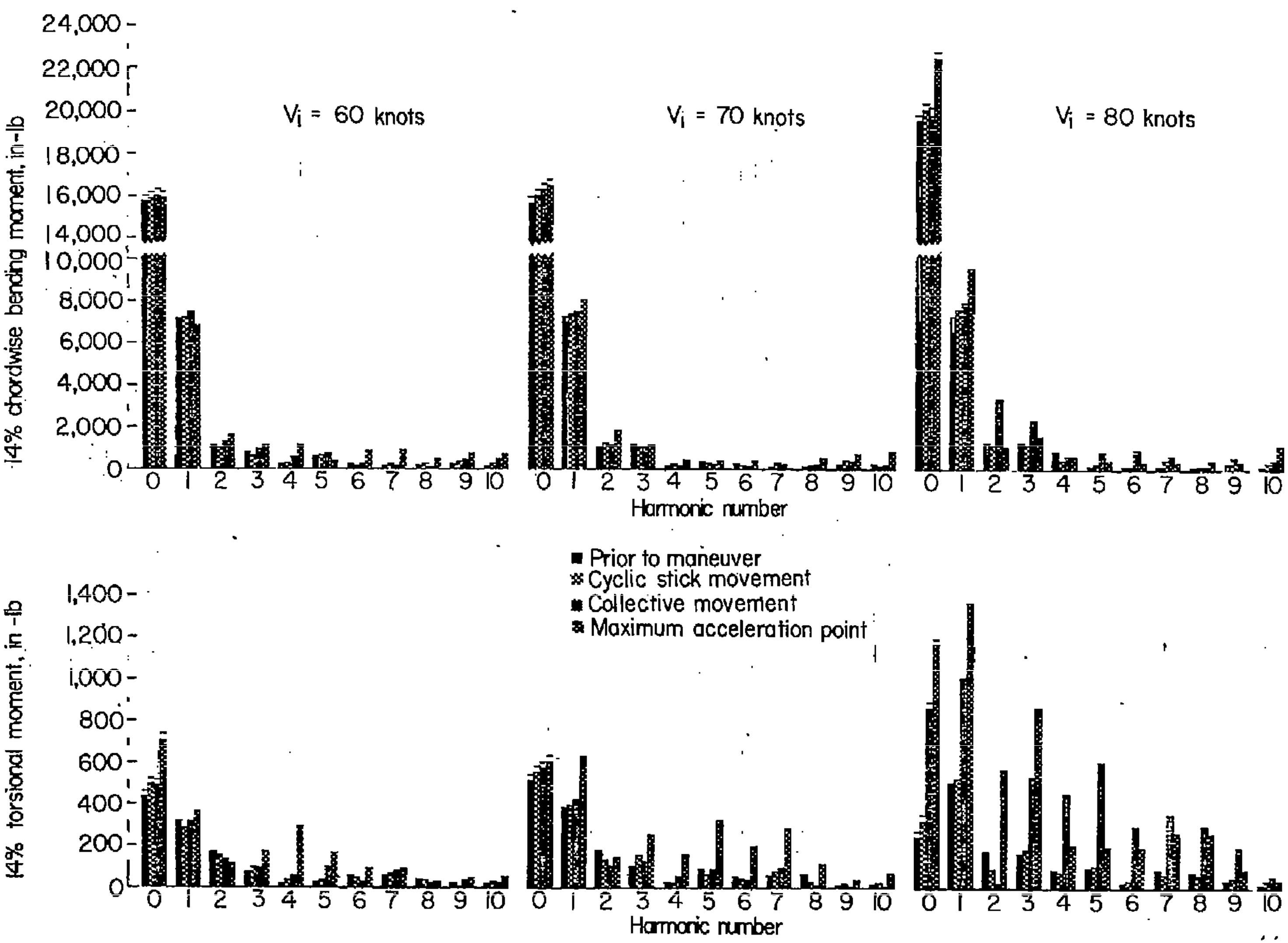


Figure 12.- Concluded.